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DEVELOPMENT OF HIGH TEMPERATURE ELECTRO-MAGNETIC ACTUATORS (HTEMA) FOR AIRCRAFT PROPULSION SYSTEMS (PREPRINT)

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**Engine Systems Branch
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14. ABSTRACT Future more electric aircraft (MEA) will require electric actuation systems for control surfaces, and engine controls. Electric motors, drive electronics, and mechanisms are essential elements of aircraft actuation in MEAs that incorporate electromagnetic actuators (EMA). High temperature environments that are experienced in aircraft applications place demands on actuator components, materials, and insulation systems, and these higher temperatures dictate the use of new technologies and materials. RCT Systems has experience with custom motors, high-power high-density electronics, and high-temperature oil-free bearing systems. RCT is also able to evaluate, design, and implement custom high-temperature motor and mechanical systems.							
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Development of High Temperature Electro-Magnetic Actuators (HTEMA) for Aircraft Propulsion Systems

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ABSTRACT

Future “more electric aircraft (MEA)” will require electric actuation systems for control surfaces, and engine controls. Electric motors, drive electronics and mechanisms are essential elements of aircraft actuation in MEAs that incorporate Electro-Magnetic Actuators (EMA). High temperature environments experienced in aircraft applications place demands on actuator components, materials and insulation systems that dictate the use of new technologies and materials. RCT Systems has experience with custom motors, high power, high density electronics and high temperature oil free bearing systems and the ability to evaluate, design and implement custom high temperature motor and mechanical systems. This paper reviews High Temperature Electromagnetic Actuator (HTEMA) options for high temperature aircraft environments including appropriate motor types, drive and control electronics, mechanisms, materials and construction methods. These options are evaluated to identify candidates that meet the challenges of tomorrow’s more electric aircraft actuators.

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PREFACE

This SBIR Phase II High Temperature Electromagnetic Actuator for aircraft development effort has brought together many new technologies, to address HTEMA state of the art. It is RCT Systems’ belief that this technology, when properly implemented, will contribute to improved performance for the long term goal of fielding more-electric aircraft.

1.0 SUMMARY

The current generation of fighter aircraft engines use jet fuel as hydraulic fluid for actuation and thermal management of key engine actuators (fuelhydraulic actuation). The high temperature actuator environment places limitations on the thermal sink capacity of the fuel/coolant which can affect the aircraft flight envelope; hence the motivation for advanced electromagnetic actuator concepts as potential replacement for the current actuators.

Under a government contract RCT Systems has focused on the design and development of HTEMA technology for a Convergent Nozzle Actuation System (CNAS) actuator (Figure 1).

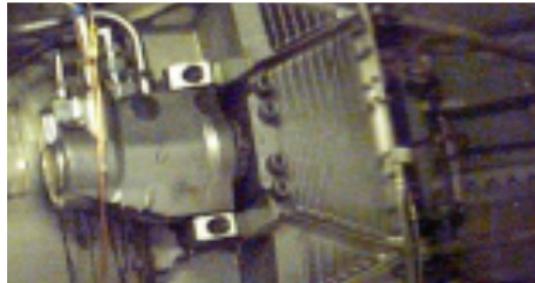


Figure 1: Convergent Nozzle Actuator¹

Efforts to design, build and test a prototype demonstrating high temperature, high reliability class of all electromagnetic actuator design with minimal/no heat load on aircraft cooling systems are ongoing. Size and weight goals are consistent with the aircraft engine limits. The actuator design is consistent with military specifications at a Technical Readiness Level (TRL) of 4-5. Actuator performance requirements are appropriate for aircraft engine applications as identified by the Air Force Research Lab (AFRL). The key technical aspects being addressed include operation in the high temperature and vibration environment, actuator force, power, weight, size, efficiency, speed, stroke, mechanical robustness and reliability, life cycle cost, failure modes and effects, and maintenance predictions.

2.0 INTRODUCTION

Engine nozzle actuation is presently accomplished using fuel as a hydraulic working fluid (hence fueldraulic) for the current generation engine actuators. While the nozzle actuation has a low duty cycle, the heat generated is continuous and presents a significant load on the aircraft/engine thermal management system.

The Air Force is interested in developing next generation actuation systems for programs such as ADaptive Versatile ENgine Technology (ADVENT), the Integrated Vehicle Energy Technology Demonstration (INVENT), and other MEA related programs.

An electrically driven actuator can reduce the heat load of the aircraft. The present engine fueldraulic actuators and aircraft fuel systems are highly inter-related leading to a challenging thermal management problem that has an impact on aircraft performance. Elimination of this fuel heat load reduces the fuel system's thermal issues. High temperature, electro-magnetic actuator component solutions that meet the technology challenges and performance requirements for an actuator system operating engine nozzle actuation have been identified.

The CNAS is the first critical application of the HTEMA technology; it provides the power to position the nozzle as required for the pilot selected engine Power Level Angle (PLA). The CNAS actuators are mounted to the aft end of the engine. Current fueldraulic actuators for the CNAS are limited by the actuator O-ring material. In the CNAS application, fluid temperature limits approach 325 °F and seal temperature limits approach 400 °F. The current engine actuators are

¹ http://en.wikipedia.org/wiki/File:F-35_engine.jpg

able to operate in a temperature environment approaching 325 °F continually and up to 560 °F for transients of 10 seconds by using the hydraulic fluid (fuel) as a means of cooling.

For the purpose of this project, the CNAS actuators are assumed to have a linear stroke of 4 inches, a combined stall load (for 4 actuators) of 42,000 lbf, and weigh about 52 lbm (actuation system hardware including routing). Envelope goals provided by the AFRL are 11 inches long by 2.5 inches high by x 6.5 inches wide. The power type is 270 VDC (see Table 1). Table 1 summarizes the actuator performance of the notional fueldraulic actuators.

Table 1: HTEMA Actuator Performance Goals

AFRL Actuator Goals		
CNAS		
Parameter	Value	Units
Force	10,500	lb _f
Stroke	4	in.
Slew Rate	2	Sec
Efficiency	TBD	%
Weight	52	lb _m
Volume	2.5 x 6.5 x 11	in.
Voltage	270	VDC
Bandwidth	TBD	Hz
Temperature	325	°F

3.0 METHODS, ASSUMPTIONS AND PROCEDURES

RCT Systems has concluded a series of technology selections, trades and sizing studies identifying the electromagnetic technologies best suited for the CNAS actuator applications. Key technologies evaluated included: Motor, Insulation, Bearings, Electronics, Gearing, Cooling and Signals and Sensors for a notional actuator (Figure 2).

Table 2 summarizes some of the technology options considered for notional actuator components with selected items highlighted in yellow. Using this trade space, RCT Systems applied the fundamental weight/space goals and performance requirements, eliminating many of the options. The best candidates for detailed design and optimization given the TRL level and COTS availability were identified. Mechanical, thermal, electrical and system analyses validated performance and established concept feasibility.

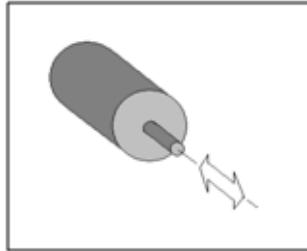


Figure 2: Notional Actuator

Table 2: Actuator Technology Options/Trades for Notional Actuator

Motor	Insulation	Gearing	Bearings	Electronics	Cooling	Signals/Sensors
Rotary/Linear	Polymer	Direct/Geared	Magnetic	Remote/Colocated	Focused Convection	Separate Wire
Variable Reluctance (VR)	Mica	Ball Screw	Active/Passive	Hi Temp/Conventional	Bleed Air	Signal on Power
DC Hi T PM	Glass	Roller Screw	Foil	SiC	Fuel Sink	
Hybrid Stepper	Ceramic	Magnetic	Bushing		Fan	Hall Device
Cu/Al Conductor	Hybrid	Mechanical	Rolling Element		Conduction	VR Resolver
Induction Cast Al/Cu		Cycloid	Ball/Roller		Thermoelectric	Sensorless Commutation
		Planetary	Ceramic/Metal		Insulation	Encoder
		Harmonic	Hybrid		Radiation Shield	Current Sensor

Development of HTEMA's for next generation aircraft could be demonstrated in the Adaptive Engine Technology Development (AETD) program, building upon the ADVENT program and focusing on risk reduction of critical engine components; maturation of an engine core; sub-scale and full-scale ground rig and engine testing; and analysis of uninstalled and installed engine performance. RCT is working with the Air Force and OEM contacts to ensure that relevant technologies/components developed under this HTEMA program can be applied to these upcoming programs.

4.0 RESULTS AND DISCUSSION

The following discusses the sizing trades and key aspects of the baseline actuator design.

4.1 Baseline Sizing Trade

The notional CNAS HTEMA employs five actuators each capable of 10,500 lbs (46.7 kN) of force producing a total of 42,000 lbs (186.8 kN) with one actuator missing. Given the requirement for an electromagnetic solution, a direct drive actuator was considered first.

Aerospace machines typically develop a pressure of 3-5 psi² in the air gap due to magnetic fields. This dictates a gap area of at least 2.1×10^3 in² is needed to generate the required force. Assuming a cylindrical geometry, Figure 3 shows the actuator gap diameter versus length relationships. Based on the 5 psi curve, an actuator with an 18 inch gap diameter has roughly a 2 foot outer diameter

² "Brushless Permanent Magnet and Reluctance Motor Drives", T. J. E. Miller, 1993, Oxford University Press, ISBN 0-19-859369-4

and 3 foot length. An approximate actuator weight would be greater than 1000 lbs which is clearly unacceptable for this application. Given the envelope requirement of 11 inch long by 2.5 inch high by x 6.5 inch wide an 11 inch long machine would have over a 60 inch diameter, an unacceptable result.

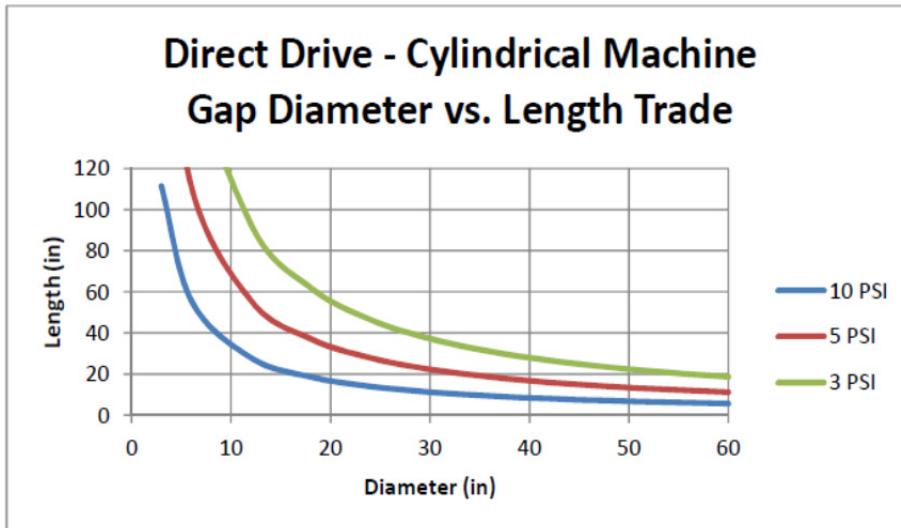


Figure 3: EM Actuator Gap Trade

Therefore, the CNAS application requires mechanical advantage to decrease the required electromagnetic actuator force and size, while increasing speed.

The Navy investigated electromagnetic actuator replacements for hydraulic cylinders in 2004³ and found planetary roller screws to be a good candidate for rotor to linear conversion and mechanical advantage. Table 4 compares the attributes of rotary to linear conversion devices.

Typical COTS roller screw ratings, summarized in Table 5, indicate a screw diameter in the 30 to 48 mm (~1.2 to 1.9 in) range is appropriate. Table 6 & Figure 4 highlight candidate roller screw geometries. The roller nut OD is on the order of 60 to 80 mm (2.4 to 3.1 in). This range is at or beyond the envelope, but is workable in the application. A custom roller screw can be designed to meet the envelope if necessary later in the program.

³ "Linear Actuator Using the Switched Reluctance Motor", Marckx, Dallas A., STTR Phase I, 2004, ONR Contract No. N00014-03-M-312

Table 4: Rotary to Linear Device Comparison⁴

	Roller Screws	Acme Screws	Ball Screws	Hydraulic cylinders	Pneumatic cylinders
Load ratings	Very High	High	High	Very High	High
Lifetime	Very long, many times greater than ball screw	Very low, due to high friction and wear	Moderate	Can be long with proper maintenance	Can be long with proper maintenance
Speed	Very high	Low	Moderate	Moderate	Very high
Acceleration	Very high	Low	Moderate	Very high	Very high
Electronic Positioning	Easy	Moderate	Easy	Difficult	Very Difficult
Stiffness	Very high	Very high	Moderate	Very high	Very low
Shock Loads	Very high	Very high	Moderate	Very high	High
Relative Space Requirements	Minimum	Moderate	Moderate	High	High
Friction	Low	High	Low	High	Moderate
Efficiency	>90%	approx 40%	>90%	<50%	<50%
Installation	Compatible with standard servo electronic controls	User may have to engineer a motion/actuator interface	Compatible with standard servo electronic controls	Complex, requires servo-valves, high pressure plumbing, filtering pumps, linear positioning and sensing	Very complex, requires servo-valves, plumbing, filtering, compressors, linear positioning and sensing
Maintenance	Very low	High due to poor wear characteristics	Moderate	Very high	High
Environmental	Minimal	Minimal	Minimal	Hydraulic fluid leaks & disposal	High noise levels

Table 5: COTS Roller Screw Ratings (PRS)⁵

Screw Dia	Lead ¹	Dynamic Load Rating	Static Load Rating	Lead Accuracy
mm	mm	kN (lbf)	kN (lbf)	
27	5 (0.20)	70.3 (15,804)	116.4 (26,168)	G5
	10 (0.39)	95.7 (21,514)	117.4 (26,393)	G5
	5 (0.20)	90.7 (20,390)	147.5 (33,159)	G5
30	10 (0.39)	88.1 (19,806)	150.8 (33,856)	G5
	20 (0.79)	106.7 (23,987)	153.8 (34,575)	G5
	8 (0.31)	220.7 (49,615)	442.7 (99,523)	G5
48	15 (0.59)	219.3 (49,301)	415.7 (93,453)	G5
	6 (0.24)	257.7 (57,933)	474.9 (106,761)	G5
	12 (0.47)	221.3 (49,750)	510.8 (114,832)	G5
60	30 (1.18)	284.5 (63,958)	530.5 (119,261)	G5

⁴ <http://www.exlar.com/pages/3-Roller-Screw-Basics>

⁵ http://www.exlar.com/product_lines/26-PRS-PRR-Series-Roller-Screws

Table 6: COTS Roller Screw Geometry⁶

Dia/Lead	do	d1	d2	D1	D2	D5	D6	D7	L1 ¹	L1 ²	L3	L4	L5	L6	L7	L8
27 x 5	27	27.28	26.49	53	50	7	83	68	65	79	23.5	55.2	20	5	22	55
27 x 10	27	27.52	25.98	53	50	7	83	68	65	79	23.5	55.2	20	5	22	55
30 x 5	30	30.37	29.66	62	58	9	92	77	71	85	29	64.7	20	6	27	64
30 x 10	30	30.49	28.99	62	58	9	92	77	71	85	29	64.7	20	6	27	64
30 x 20	30	30.49	28.99	62	58	9	92	77	71	85	29	64.7	20	6	27	64
48 x 8	48	48.40	47.35	86	80	11	122	104	113	127	45	88.7	45	6	35	88
48 x 15	48	48.90	46.84	100	89.97	13.5	150	127	113	127	45	103	45	8	37	102
60 x 6	60	60.37	59.56	110	100	13.5	150	130	106	124	47	113.2	40	8	30	112
60 x 12	60	60.67	59.05	110	100	13.5	150	130	106	124	47	113.2	40	8	30	112
60 x 30	60	61.24	58.25	110	100	13.5	150	130	106	124	47	113.2	40	8	30	112

1 without wipers
2 with wipers
3 overall length of nut for double-nut configuration without wipers
4 overall length of nut for double-nut configuration with wipers

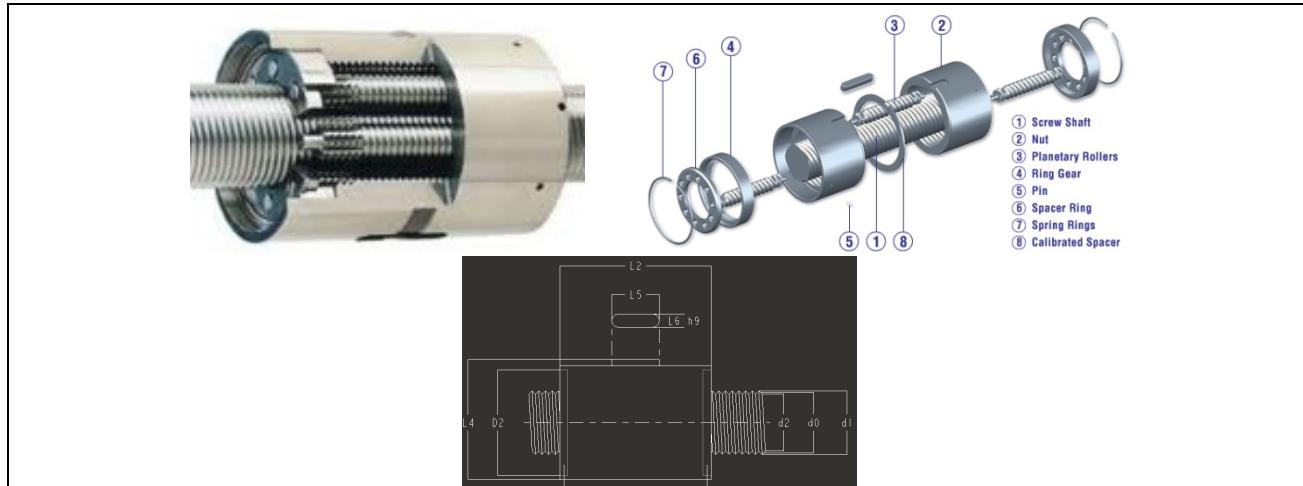


Figure 4: COTS Roller Screw Geometry^{7,8,9}

Assuming a 30mm (~1.2 inch) diameter screw there are three COTS leads available; 5, 10 & 20 mm per revolution (~0.2, 0.4 & 0.8 inch/rev) . For a 4 inch stroke (~102 mm), the number of revolutions required are approximately 20, 10 and 5 respectively. Likewise for a 48 mm (~1.8 inch) diameter screw there are 8 and 15 mm per revolution leads available. This translates to 12.8 and 6.8, revolutions respectively.

Table 7 summarizes the, torque, average and peak speed the roller screws of various leads must perform at to meet the CNAS requirements, assuming a trapezoidal velocity profile. This summary shows low speeds and high torques, so the motor will be large and inefficient as shown

⁶ http://www.exlar.com/product_lines/26-PRS-PRR-Series-Roller-Screws

⁷ http://www.google.com/imgres?imgurl=http://img.directindustry.com/images_di/photo-g/planetary-roller-screw-205378.jpg&imgrefurl=http://www.directindustry.com/prod/skf-linear-motion/planetary-roller-screws-320-205378.html&h=600&w=602&sze=87&tbnid=ft8dkkpc-b3RrM:&tbnh=90&tbnw=90&prev=/search%3Fq%3Dplanetary%2Broller%2Bscrew%26tbnm%3Disch%26tbo%3Du&zoom=1&q=planetary+roller+screw&docid=moH3wq_O0X4S8M&hl=en&sa=X&ei=3VV3T9iAOKTg0QHVI9mWDQ&sqi=2&ved=0CGIQ9QEwBA&dur=16

⁸ <http://www.google.com/imgres?imgurl=http://www.nookindustries.com/images/NRExploded.jpg&imgrefurl=http://www.nookindustries.com/rollerscrew/RollerScrewGlossary.cfm&h=304&w=590&sze=99&tbnid=MYYxTNTy0R0EJM:&tbnh=70&tbnw=135&prev=/search%3Fq%3Dplanetary%2Broller%2Bscrew%26tbnm%3Disch%26tbo%3Du&zoom=1&q=planetary+roller+screw&docid=26umk7OwV2mY4M&hl=en&sa=X&ei=3VV3T9iAOKTg0QHVI9mWDQ&sqi=2&ved=0CFwQ9QEwAg&dur=297>

⁹ <http://shell.windows.com/fileassoc/0409/xml/redir.asp?EXT=dwg>

in Figure 5. Assuming a ~3:1 length to diameter ratio, the motor would weigh on the order of 50 lbs.

Table 7: Roller Screw - Lead Trade Summary

Requirement						
	Parameter	Value	Unit	Value	Unit	
	Stroke	4.0	in	101.6	mm	
	Time	2.0	seconds	0.03333	min	
	Force	10500	Lb	46704	N	
Result						
Lead	Lead	Rev	Average Speed	Peak Speed	Torque	Torque
mm/rev	in/rev	rev/stroke	RPM	RPM	in Lb	Nm
5	0.197	20.3	610	1219	2066.9	233.5
10	0.394	10.2	305	610	4133.9	467.0
20	0.787	5.1	152	305	8267.7	934.1

Inclusion of a single pass, 5 to 1 planetary gear between the planetary roller screw and motor improves this situation, as summarized in Table 8. COTS planetary gears show a significant performance advantage for a small weight (<2.8 lbs). Issues with dry lubrication, life and seals must be addressed in a custom detailed design for this high temperature application. However, this information is sufficient for trade studies. Assuming a ~3:1 length to diameter ratio again, the motor weight is less than 12 lbs. COTS planetary gear gearing data below shows standard ratios, envelopes, properties and performance data.

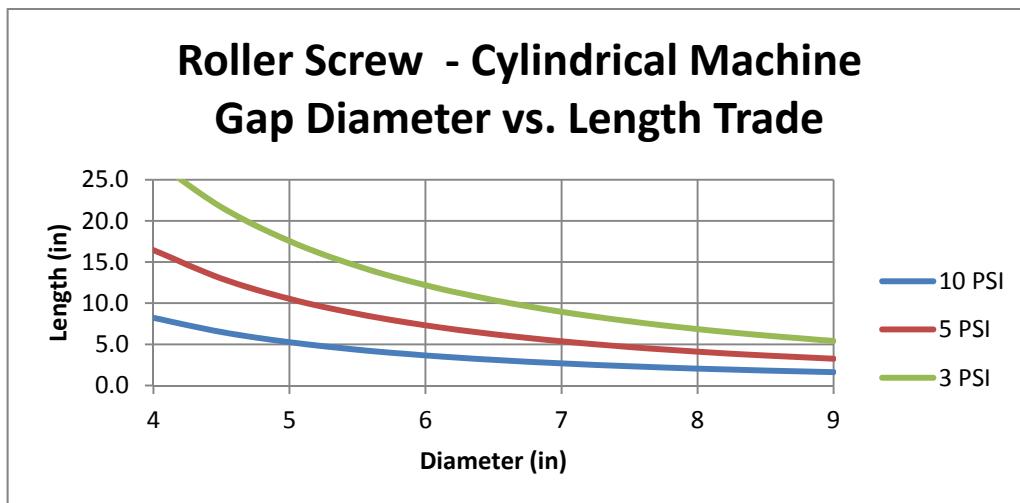


Figure 5: EM Actuator with Roller Screw Motor Gap Trade

Table 8: Roller Screw with 5:1 Planetary Gear - Lead Trade Summary

Lead mm/rev	Lead in/rev	Rev rev/stroke	Gear Ratio	Average Speed RPM	Peak Speed RPM	Torque in Lb	Torque Nm
5	0.197	20.3	5	3048	6096	413.4	46.7
10	0.394	10.2	5	1524	3048	826.8	93.4
20	0.787	5.1	5	762	1524	1653.5	186.8

Harmonic drives (a.k.a., flex splines) were considered for higher gear ratios in smaller packages. However, concerns about the ability to back drive the unit in some failure modes prevented inclusion in the baseline design at this juncture. Magnetic gearing is also an option but concerns about PM demagnetization during flux reversals at high temperature were considered high risk.

It must be noted that slightly higher torques are required from the motor than Tables 7 and 8 indicate; torque losses due to contact angles and drags in the mechanisms must be added. A $\sim 1.1x$ torque factor for these effects has been included in detailed designs. Comparison of Figure 6 with Figure 3 shows the advantages of the planetary roller screw and planetary gear, even at this preliminary trade level. A preliminary weight budget has been established from this preliminary trade as summarized in Table 9.

Care must be exercised in the lead screw and gear ratio selection if the actuator must be back driven with the power off. There are is a critical angle in lead screws where the unit will act as a friction lock at and below the critical value. Similarly, the gearing will multiply any drag and cogging torques present in motor which can also inhibit the ability to back drive an actuator. It is important to keep this in mind during detailed trades.

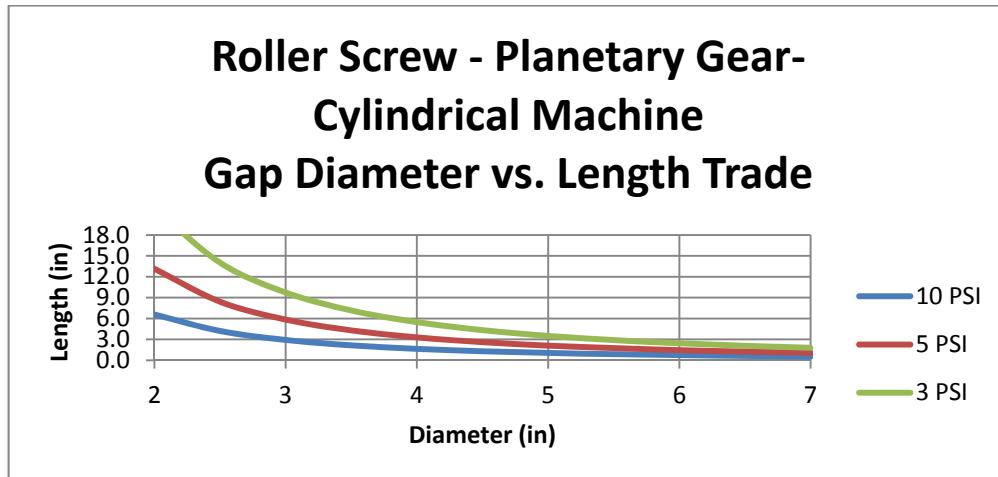


Figure 6: EM Actuator with Roller Screw and Planetary Gear Gap Trade

4.2 Baseline Actuator Concept

Based on trade and sizing analysis to date and the initial constraints, RCT Systems is designing a system which includes the following key components and technologies: Roller Screw, Planetary Gearing, High Temperature Coatings, High Temperature Motor Materials & Insulation System, High Temperature Power Electronics, and Sensors that meet the AFRL envelope requirements. The following describes key sub-component considerations.

4.3 EM Machine Types

Several motor types have been considered with high efficiency and minimal weight and volume; these include surface mount permanent magnet (PM), Halbach Array PM, buried magnet PM, and hybrid stepper. Others that do not require PMs include wound rotor DC (brush and brushless), Variable or Switched reluctance (VR or SR) machines and squirrel cage induction motors. Trades have identified Brushless DC PM and SR machines are of primary interest. Both motors can use sensorless commutation methods. A VR resolver can be incorporated in the design if required for control feedback but this requirement is not anticipated at this time.

VR motors are robust, with simple windings, facilitating application of high temperature insulation. Because VR motors have no permanent magnets they do not generate a back Electro Motive Force (EMF) voltage when unpowered, which may be advantageous in some failure modes. An ONR Phase I study on a linear actuator¹⁰ selected a VR machine in a marine environment because weight was not as much of an issue and the servo loop was less demanding than in aircraft applications.

The PM motor design includes a band to contain the surface mount PMs. VR machines do not require such containment requirements but have quite small mechanical gaps that must be maintained over temperature and life. Both machines can be back driven, with VR machines having an advantage of no back emf generated when unpowered. This may be an advantage in failure modes and effects analyses (FMEA). Given the motor is used in an aircraft application, high saturation flux density lamination material is highly desirable.

Brushless DC PM motors won the packaging and weight/power trade and provide excellent efficiency with high bandwidth for servo applications. Brushless commutation is appropriate for life, reliability and maintenance issues. High motor pole count is a big factor in minimizing weight. Maximum slew rate, speed, switching speed and/or geometry will be the limiting factor but the higher the number of poles, the better.

¹⁰ Marckx, D.A., STTR Phase I Final Technical Report, Linear Actuator Using the Switched Reluctance Motor, ONR Contract No. N00014-03-M-312, 02 Feb, 2002.

4.4 Gearing

Mechanical gears are a mature technology with a long and rich history. When properly designed, applied, and maintained they can provide long, failure free performance. In addition, cost and manpower limitations are pushing hardware toward more robust, no maintenance technologies.

Planetary gears were selected in the baseline design for their power dense, high torque transmission capacity and form factor. A COTS gear head was identified with 5:1 gear ratio, in a single pass. Modifications to the COTS gear head with a 98%- 95% efficiency for a single pass and 150,000 to 200,000 Hours of life at room temperature to meet the high temperature environment are anticipated. Flex spline or harmonic drives can also be used if failure modes and effects analyses show their inability to be back driven is not an issue.

4.7 HTEMA Simulation Study

A simulation study of HTEMA has been performed based on flow down requirements. The simulation tool used is Simulink together with its SimPowerSystems (SPS) toolbox.

Instead of using SPS library models, custom models have been created for the permanent magnet synchronous motor, the motor drive, and some of the mechanical elements. The main reason for creating custom models is that the existing SPS models do not provide the flexibility needed for detailed study of the HTEMA. For example, the PM machine model in the SPS library does not provide access to both terminals of the phase windings. The present HTEMA baseline design calls for two PM motors electrically connected in series and driven by a single inverter; therefore, it is necessary to have model with access to both winding terminals.

Figure 18 shows the simulation schematic. Custom models of the PM motors and the drive electronics in HTEMA are incorporated. The shafts and speed reduction devices roughly model the other components of HTEMA, i.e., the planetary gear head, the pinion gear, and the roller screw. The mechanical models are a simplified representation of the gear train in the HTEMA. The purpose is to capture the fundamental mechanical behavior without incurring intensive modeling effort. The plant is represented as a constant force only, since its mass is still to be determined.

A simple PI position controller is provided to obtain the servo behavior, so that the desired position profile can be tracked satisfying the system requirements. This controller is the outer control loop of a nested controller structure. The inner speed control loop and current regulation loop are embedded in the PM motor drive model.

As shown in Figure 7, a nested controller structure is used to provide the servo performance. The outermost control loop is the position controller, which generates the motor speed reference used by the speed controller. The speed controller calculates the motor current reference, and the innermost current controller regulates the motor current to follow this reference. All these controllers adopt the standard PI controller structure.

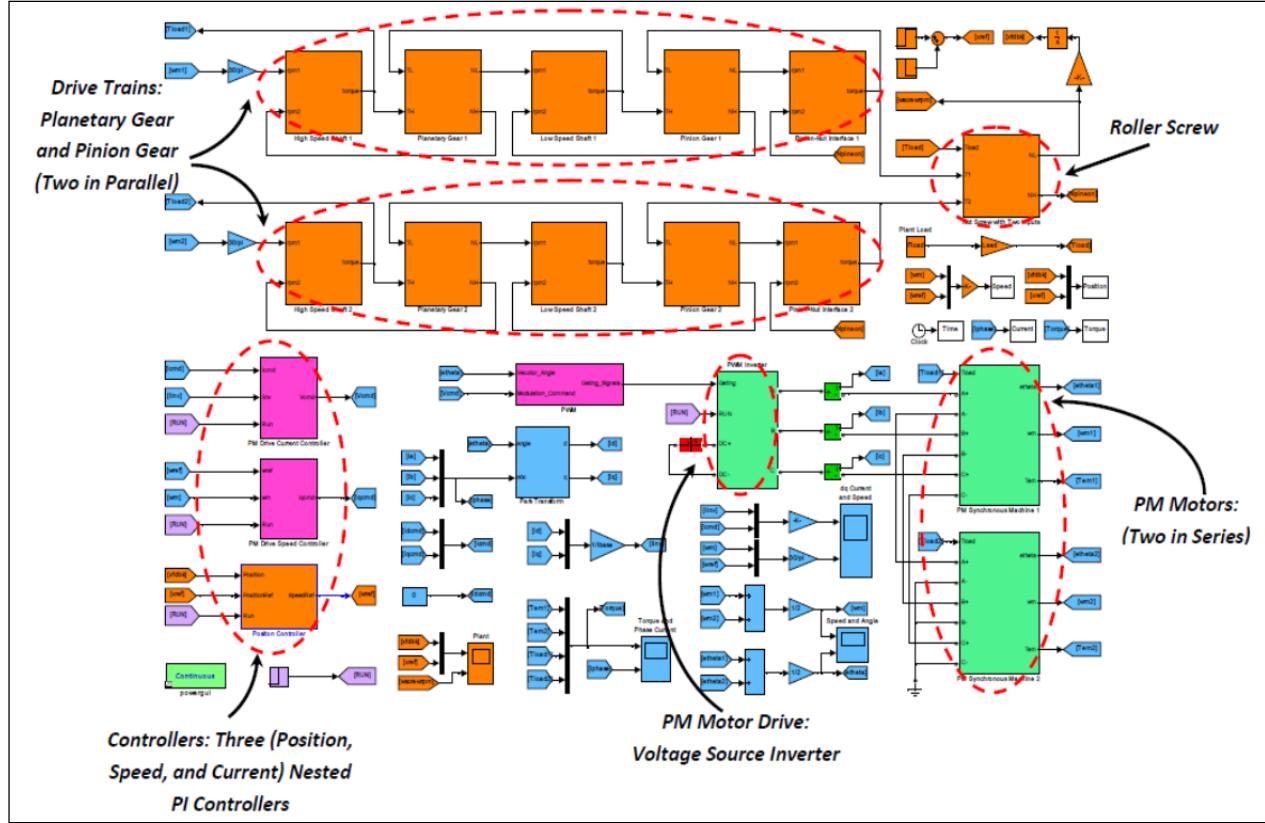


Figure 7: HTEMA Representation in Simulink®

In the following, descriptions of the major blocks shown in the HTEMA simulation schematic are provided.

The *PM Synchronous Machine* model is based on the standard three-phase PM machine equations:

$$\begin{aligned}
 L_d \frac{di_d}{dt} &= v_d - R_s i_d + \omega_e \lambda_q & L_q \frac{di_q}{dt} &= v_q - R_s i_q - \omega_e \lambda_d & J_M \frac{d\omega_m}{dt} &= T_{EM} - T_L - D \omega_m \\
 \lambda_d &= L_d i_d + \lambda_{PM} & \lambda_q &= L_q i_q & T_{EM} &= \frac{3n_{PP}}{2} [i_q \lambda_{PM} + i_d i_q (L_d - L_q)]
 \end{aligned}$$

In the above equations, the subscripts d and q indicate d - and q -axis components, respectively, λ_{PM} is the flux linkage due to the permanent magnets, R_s is the stator winding resistance, L_d and L_q are the d - and q -axis inductance, respectively, J_M is rotor inertia, D is the damping coefficient, T_L is the load torque, and n_{PP} represents the number of pole pairs. The electrical and mechanical angular speeds are related by the equation $\omega_e = n_{PP} \times \omega_m$. With this set of equations, the d - and q -axis equivalent circuits can be drawn as in Figure 8, and they form the basis of the custom *PM Synchronous Machine* block.

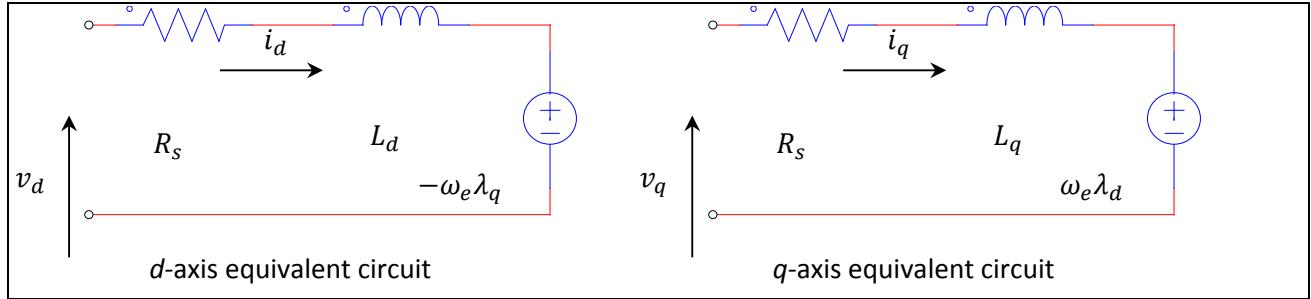


Figure 8: *d*- and *q*-axis Equivalent Circuits of the PM Synchronous Machine

The shaft block models the mechanical shaft dynamics and gear meshing with a torsional stiffness $K_{stiffness}$ and a relative damping coefficient of $B_{damping}$. The gearbox is modeled with an inertia and ideal speed reducer. The efficiency is accounted for by amplifying the load torque by a factor of $1/\text{eff}$. The shaft and gearbox models are similar to the SimPowerSystems library models, with the difference that a continuous instead of discrete model is used here.

The roller screw nut is modeled with two inputs and one output. The effect of the lead screw is accounted for by adding an extra inertia to that of the nut. The two pinions transfer the driving torque to the nut. The interface between the pinion and nut models the meshing stiffness and relative damping with an equivalent shaft model. Drive train and roller screw parameters were selected for simulation purposes. Note that some parameters are estimated values. At this stage of simulation study, only rough modeling of the drive train has been done.

A three-phase inverter bridge acts as the motor drive. The gating commands to the semiconductor switches are generated by a PWM circuit. This PWM circuit accepts the modulation commands produced by the current regulator, adds to them a common-mode component to enhance the DC link voltage utilization, and finally compares the modulation commands with a triangular carrier to generate the gating signals.

Figures 9 through 12 provide the simulation results.

Figure 9 shows the actuator tracking performance. At $t=1\text{s}$, the actuator receives a 4-inch step command. The screw is able to achieve the 4-inch stroke in less than 2 seconds. At $t=2.5\text{s}$, the actuator is commanded to return to the original position. Again, it is able to achieve this in less than 2 seconds. Figure 10 presents the motor speed profile during the above process. Also shown in Figure 12 are the speed reference generated by the position control loop.

Figure 11 provides the electromagnetic torque produced in the motor, together with the load torque transferred to the motor shaft. Note that it is assumed that the plant asserts a constant force in the system. This constant force results in a constant torque applied in the shaft system, which has to be balanced by the motor all the time in addition to any transient torque needed to accelerate or decelerate the shaft and any mechanical loss.

Figure 12 depicts the motor current waveforms. Magnitude of the current (and torque) ripple depends on the switching frequency, DC link voltage, and the machine inductance. In this simulation, the DC link voltage is maintained at 270V. A switching frequency of 25 kHz is used in the simulation.

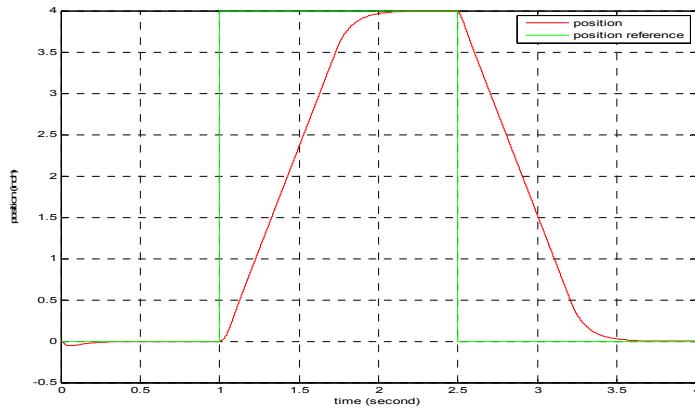


Figure 9: Tracking Performance of HTEMA

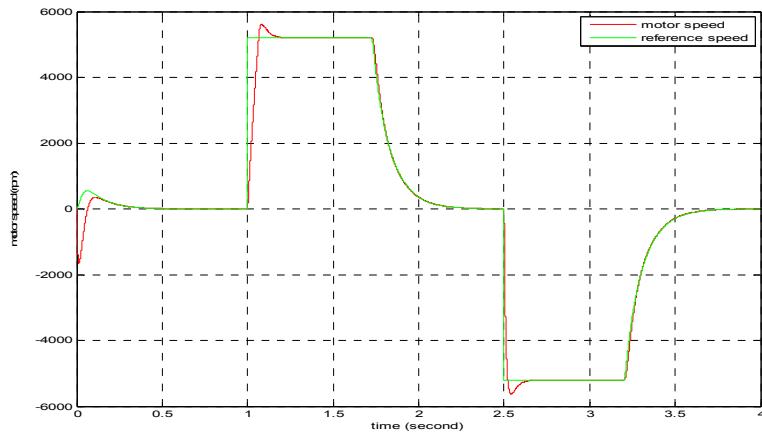


Figure 10: Motor Speed Reference and Actual Speed

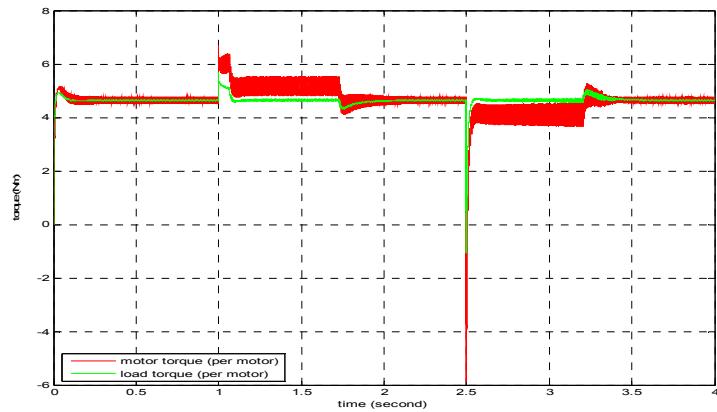


Figure 11: Motor Load Torque and Electromagnetic Torque

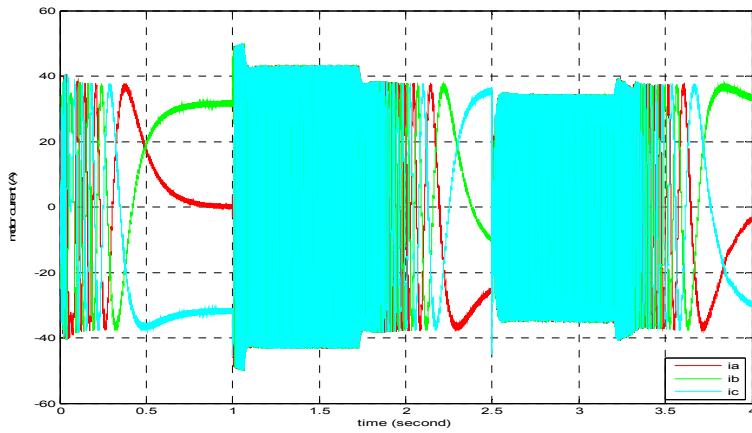


Figure 12: Motor Phase Current Waveforms

5.0 CONCLUSIONS

During the Phase I effort, SBIR Topic Number: AF112C-176 High Temperature Electro-Magnetic Actuators (HTEMA), RCT Systems completed the conceptual design and development of a High Temperature Electro-Magnetic Actuator, demonstrating feasibility of the baseline design. Key elements of the HTEMA have been investigated and the baseline design meets the space, weight and performance requirements. During the Phase II program, RCT Systems is continuing the development to mature the HTEMA system for the CNAS application, perform detailed design, build and test a prototype unit demonstrating compliance with USAF goals and validate analytical models. This work will lead to efforts that transition the HTEMA to military flight certified hardware supporting future engine upgrades, and commercial aviation applications.



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Development of High Temperature Electro-Magnetic Actuators (HTEMA) for Aircraft Propulsion Systems

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Outline

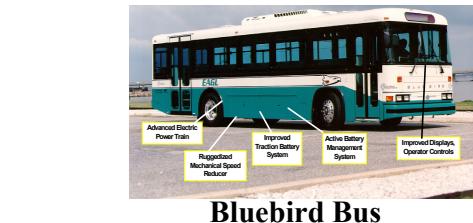


- RCT Systems Overview
- Introduction to HTEMA's
- Requirements
- HTEMA Concept
- Conclusion

2

Power Systems Technology – Applications - Products

Technology

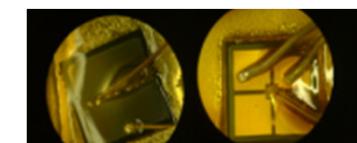


RCT Systems
(Defense/Aerospace)
2010

2003
Subsidiary
Corporations

Magmotor &
Electronics
2008

InverPower
2001



SiC Devices



PV Inverter



Navy Power
Converter Modules

**Patriot -
1992**

**1985 MIT-
DRAPER**



FMI & HiComp
1998

Magmotor
1997

Beacon
Power
1997

Applications

Modular Power
Electronics

Electric Machines
& Magnetics

High Bandwidth
Controls

Packaging & Thermal
Management

Capabilities/Facilities

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Assembly & Test Lab**

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 - Packaging and Thermal Management
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Introduction



This presentation is an overview of work performed under an AFRL SBIR Contract for topic AF112C-176
“High Temperature Electro-Magnetic Actuator (HTEMA)”



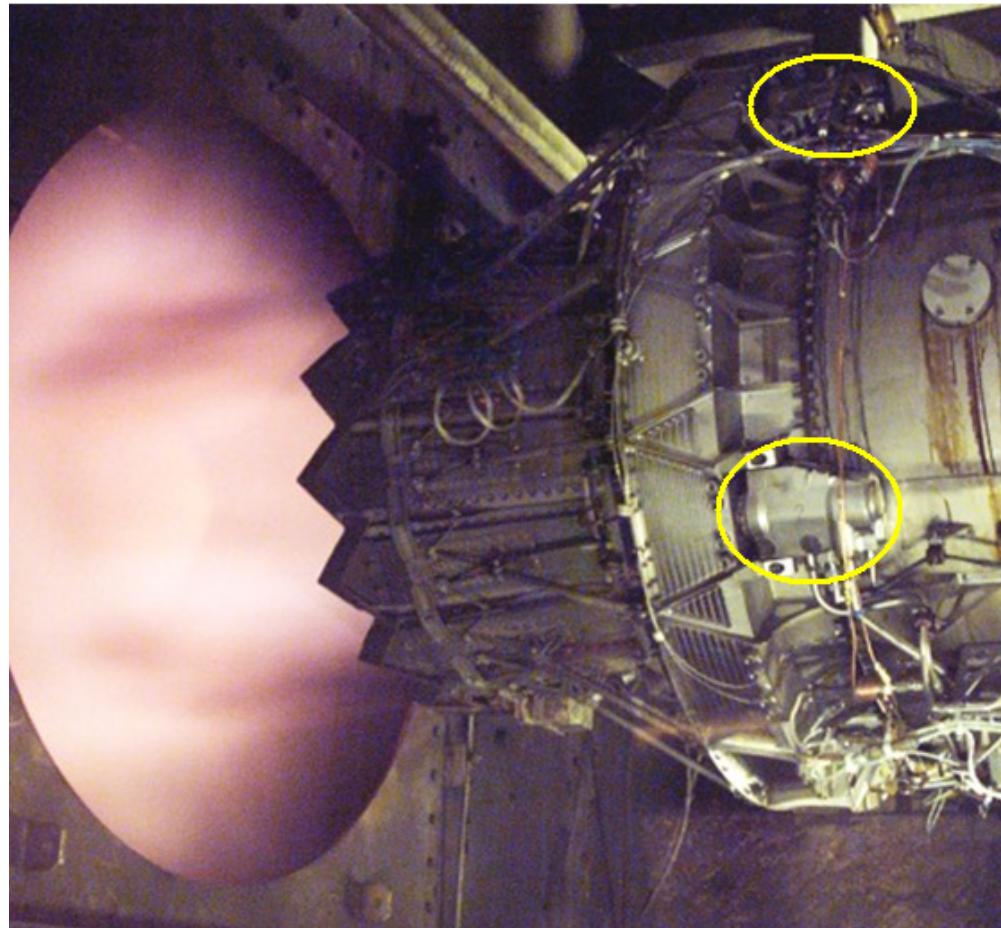
Background: Critical EMA's



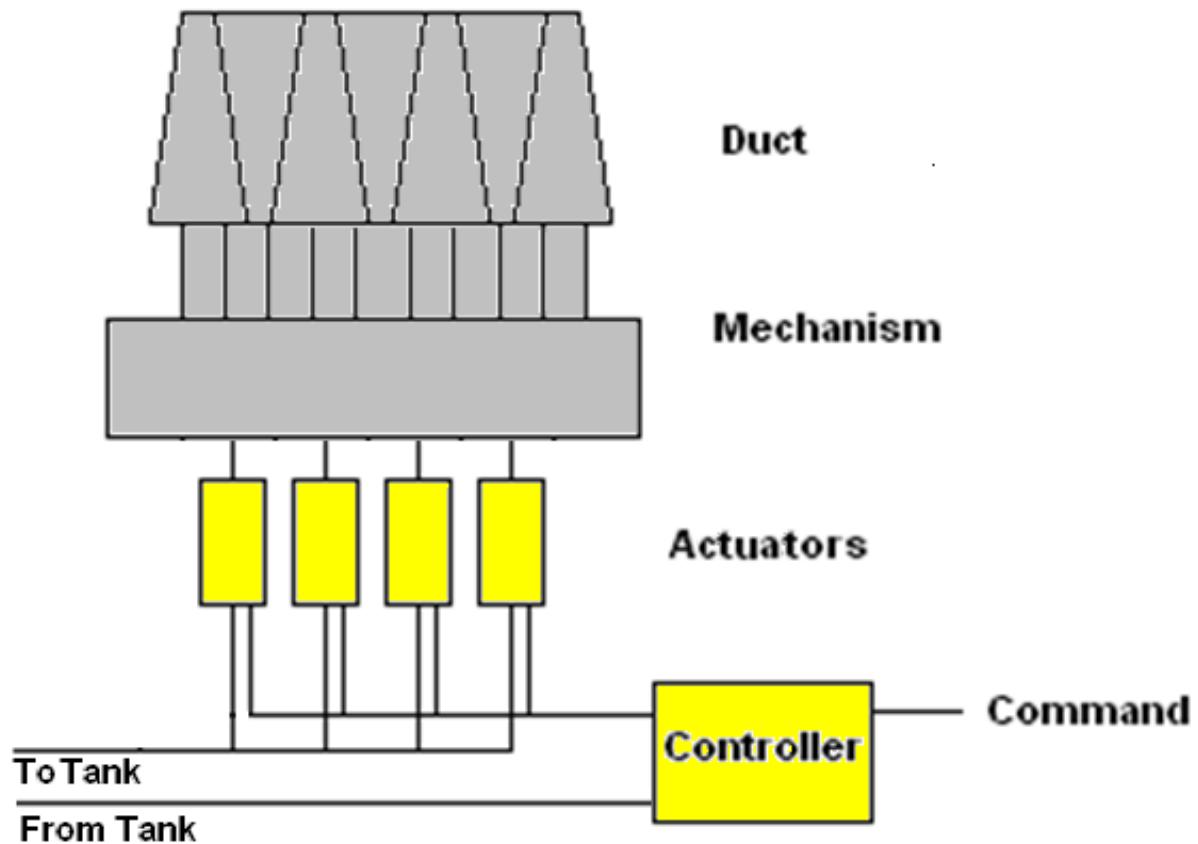
- Actuators provide the mechanical power to position a mechanism based on selected engine power levels.
- The actuators are mounted to the aft end of the engine.
- Engine nozzle actuation is presently accomplished using a working fluid in hydraulic actuators that circulates to keep parts cool.
- Nozzle actuation has a low duty cycle, but the heat generated is a continuous, and significant, load on the systems thermal state.
- An electrically driven high temperature actuator can reduce the heat load, because no fluids are need for cooling, reducing the thermal load on the system.

Phase II Will Demonstrate a Prototype HTEMA System in a Representative Environment

Actuator Locations



Actuator System Layout





Summary of Performance Goals



ACTUATOR GOALS		
	HTEMA	
Parameter	Value	Units
Force	10500	Lbf
Stroke	4	in
Slew Rate*	2	Sec
Efficiency	TBD	%
Weight	52	lbm
Volume	2.5x6.5x11	in
Voltage	270	V DC
Bandwidth	TBD	Hz
Temperature	>325	°F
* To Be Confirmed		

Current Actuator Application Technical Considerations

- **Temperature:** Existing actuators are limited by the “O”-ring material and fluid temperature limits
 - The fluid temperature limit approaches 325 °F
 - The seal temperature limits approach 400 °F
 - Transients reach 560 °F for 10 seconds
- **Weight & Volume:** are critical in the application
- **Operational Considerations:** The actuators are located on other mechanisms and must move during operation
 - **HTEMA Actuators (RCT's Focus)**
 - Linear actuators
 - 4 inches Stroke
 - 42,000 lbf Combined 4 Actuators Load
 - 52 lbfm Weight Actuation System Goal
 - Envelope requirements
 - 11 inch long x 2.5 inch high x 6.5 inch wide

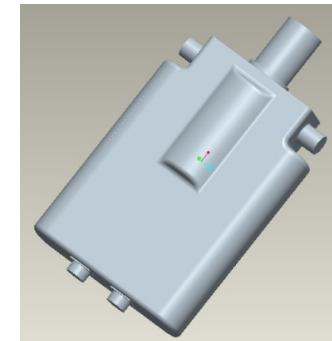
Phase I Objective & Results

Objective:

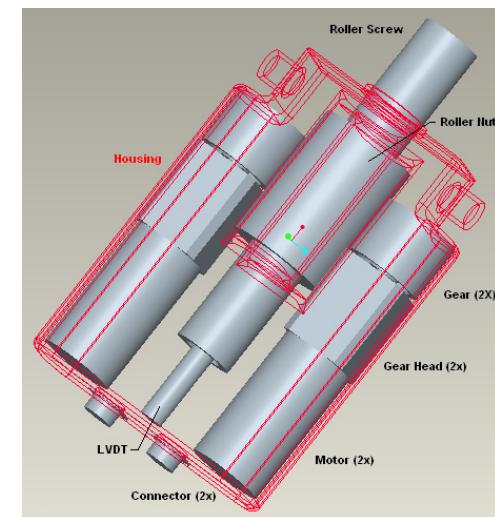
Feasibility demonstration of a HTEMA system delivering the same or better baseline servo performance with no heat load on the system.

Results:

- Completed HTEMA System Architecture Trades
- Selected Roller Screw with Geared Brushless DC Motors
- Employ High Temperature Power Electronics
- Packaged to Meet Existing Form Factor and Interface
- Electrically Controlled Servo Loop
- Concept for Fault Detection and Health Monitoring
- Concept Design Feasibility and High Efficiency Shown
- Completed Preliminary System Design and Analysis



Actuator Package
Outline



Interior View

Simulation Results

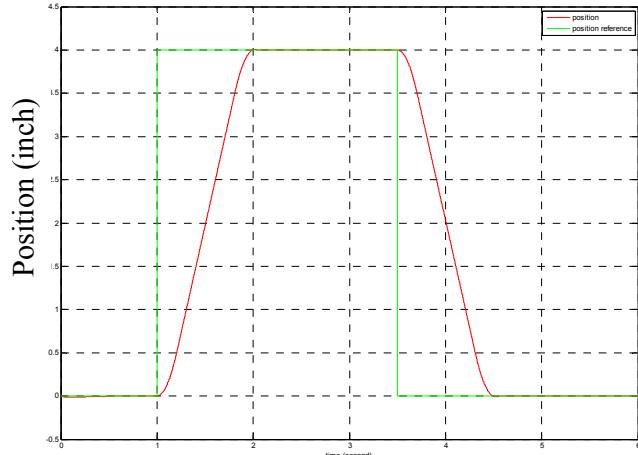


Figure 1

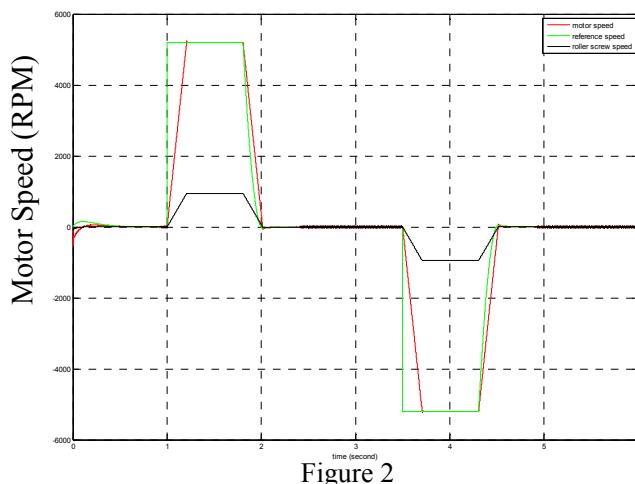


Figure 2

- Figure 1 shows the actuator tracking performance. At $t=1$ s, the actuator receives a 4-inch step command. The screw is able to achieve the 4-inch stroke in less than 2 seconds.
- Figure 2 presents the motor speed profile during the above process.
- Figure 3 provides the electromagnetic torque produced in the motor, together with the torque command generated by the speed control loop within the PM motor drive model.

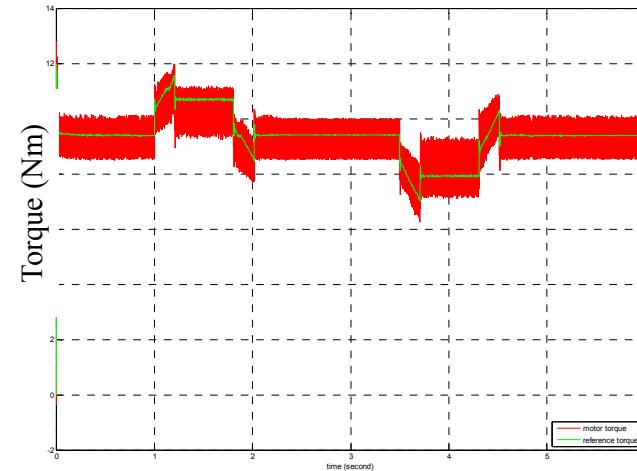
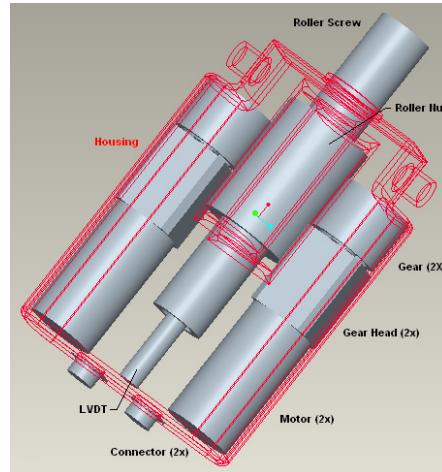


Figure 3

HTEMA Concept Hardware Validation & Test Rig

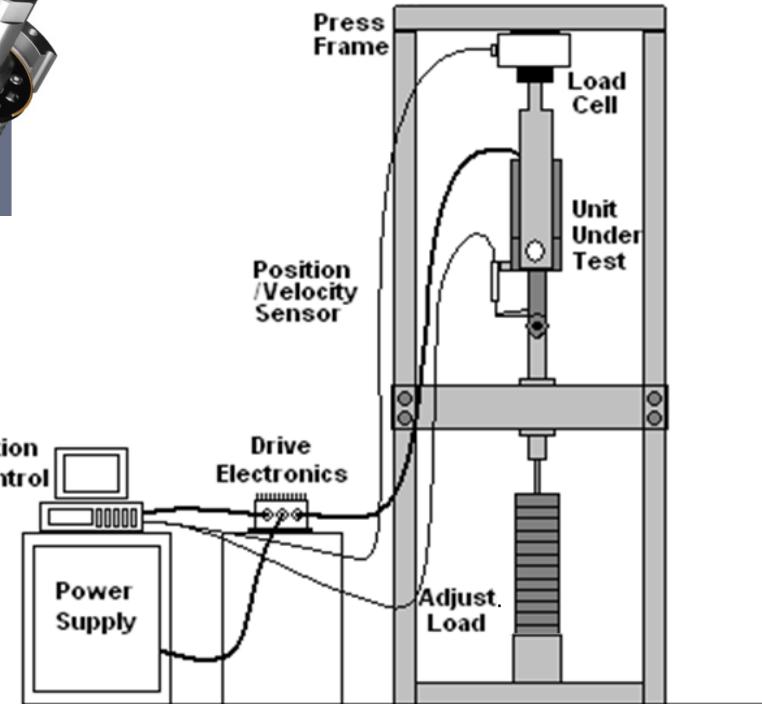
Baseline Actuator Configuration



Roller Screw



Open Loop Test Rig



TRL Levels: TRL-4 end of FY 13; TRL-6 end of FY 14



Conclusions



- HTEMA Technology is feasible in this application
- Development work continues in the Ph II SBIR

Questions

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15

30

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